# Magnetostrictive and Electrostrictive Industrial Ultrasonic Apparatus

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THE industrial uses of high-intensity sound waves far above audible frequencies are finding new practical applications. The 50-year-old field of ultrasonics has produced a great deal of theory but, to date, very few commercially useful devices. Sonar is the outstanding military application, and much know-how has been locked up in Government laboratories.

This article describes three ultrasonic devices of known commercial utility. These devices will do jobs which are either impossible or impractical to do with conventional equipment. The 10-kc magnetostrictive oscillator can clean small complicated mechanical parts such as precision ball bearings more thoroughly, and faster, than ever before. An ultrasonic machine tool provides a device for machining complicated forms in the super metals and ceramics without using the critically short-supply and expensive diamond dust. For a new chemical catalyst, and medical therapy, the 1-mc electrostrictive equipment closes the gap a little further between the theoretical and the practical application of ultrasonics.

## A magnetostrictive oscillator

The Raytheon 200-watt 10-kc magnetostrictive oscillator, model DF-101, was designed as a research tool primarily for the science laboratory and may be used to vibrate a sample of liquid at a frequency of approximately 10 kilocycles. However, it is finding application in industry for cleaning small parts.

The magnetostrictive oscillator consists of a driver unit and a treatment unit, Fig. 1. The treatment unit consists of a covered cup for holding samples. A vibrating diaphragm serves as the bottom of the cup. A laminated nickel rod is attached to the bottom of the diaphragm, and the field coil for magnetizing the rod is encased in a stand which is also used to hold the rod and cup.

The driver unit generates the ultrasonic electrical power which is fed to the field coil in the stand. A special push-pull electron-coupled oscillator is used to eliminate oscillator detuning due to changes in the load. The a.c. oscillations developed in the grid circuits of the oscillator tubes are coupled to the low-impedance load in the plate circuit with a step-down transformer. Because of the push-pull arrangement, core losses and second harmonic distortion are considerably decreased over single-tube operation. Maximum trans-

Fig.1—10-kc magnetostriction oscillator.

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of power to the field coil is effected by means of a filter circuit which balances out the reactive component of the load. The a.c. signal from the electrical oscillator is then superimposed upon a d.c. polarizing current supplied from a rectifier and together they are passed through the energizing coil in the stand.

## A magnetostrictive motion

When a d.c. magnetic field is set up in a bar of magnetostrictive material, it expands or contracts parallel to the axis of the magnetic field. The permalloys expand while pure nickel contracts. With flux densities of a few thousand gausses, this contraction or strain in the material is about $10^5$, or 1 part in 100,000. When, in addition, an a.c. signal is passed through the same coil of wire, the resulting alternating magnetic field causes the bar to periodically shorten and expand about the contracted length whose value is determined by the polarizing current. If the frequency of the alternating current is equal to the resonant frequency of the bar, its resultant motion is also a resonance phenomenon and the d.c. strain of $10^5$ may be multiplied 10 or 100 times depending on the effective Q of the material. Laminations are used to cut down the eddy-current losses which are proportional to the square of the frequency, flux density, and the thickness of the individual core laminations. Besides a magnetic hysteresis loss which is common to all magnetic materials, there is also an elastic hysteresis loss. In other words, a material which is subjected to alternate expansion and contraction exhibits a stress-strain loop similar to the familiar hysteresis loop.

The nickel laminations are used in producing the oscillations, for the following reasons: (1) A-type nickel, properly heat treated, has as high an electromechanical coupling factor (a figure of merit which relates the amount of electrical energy converted into mechanical energy) as any known magnetostrictive material. (2) Nickel is as rugged as the other materials and a lot easier to work with from an annealing as well as machining point.

The motion or amplitude developed

phragm which drives the liquid to be treated. As long as the diameter of the diaphragm is less than the wavelength of sound, as it is in the 10-kc unit, the sound waves spread out uniformly in all directions from the sound source so that the intensity in the direction normal to the axis of motion is only slightly less than the intensity along the axis. In other words, the action is essentially nondirective. The liquid is contained in a special cup which is adapted to maintain the temperature of the treated liquid relatively constant by means of a water jack. After flowing through the jacket the water serves to cool the magnetostrictive stack by spraying inside the enclosed stand. Since the magnetic properties of nickel deteriorate with increasing temperature, this water spray is necessary for best operation. A cap prevents the escape of any liquid when subjected to violent agitation and decreases the intensity of the sound radiated to the air.

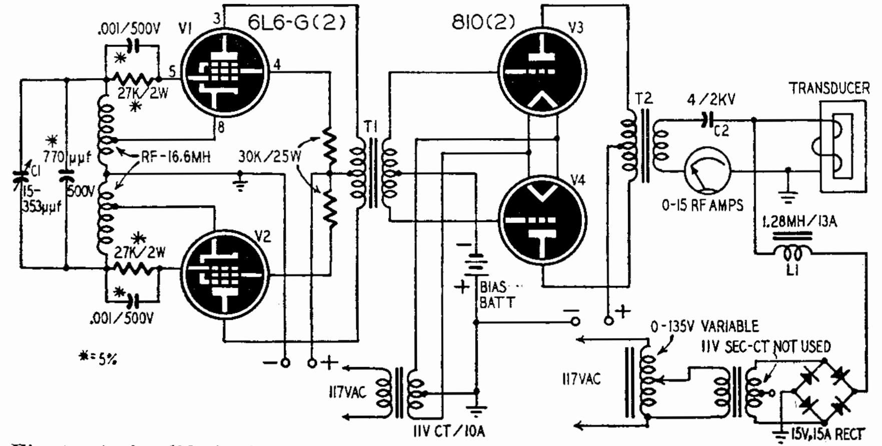

Fig. 2—A simplified schematic diagram of electronic driver and control equipment.

## The generation of cavitation

From a physical point of view, a major use of the 10-kc oscillator is its ability to cavitate liquids. The phenomenon of cavitation, which has long been one of the unknown quantities in engineering, is being attacked theoretically as well as experimentally by a number of laboratories. Present results indicate that when high-amplitude sound waves are transmitted to a fluid, the mechanical strain in the liquid becomes so great that the liquid is torn apart. Under steady-state conditions, light liquids filled with air cavitate when the negative acoustic pressure reaches the atmospheric pressure. In terms of power density transmitted by the diaphragm to the fluid, the power required to cavitate liquid at atmospheric pressure is only ⅓ of a watt per square centimeter. Power densities of the order of 25–50 watts per square centimeter are available from the 10-kc unit. Cavitation point depends on frequency. For a fixed amplitude of sound, it is easier to cavitate at low frequencies.

Major uses of the 10-kc equipment to date have been in the cleaning of small metal parts, bacteria disintegration, and the emulsification of immissible liquids. The vibrating diaphragm may size or shape instead of the cup, thus facilitating the treatment of larger parts or the installation of continuous-flow apparatus. The standard cup supplied will hold about 150 cc.

## An ultrasonic machine tool

Another magnetostrictive device is the Raytheon ultrasonic machine tool which utilizes electronics and ultrasonics in a combination providing a unique machine tool capable of many operations which have in the past been impractical. The essential parts of the apparatus are the electronic driver and control unit, the transducer which converts electrical into mechanical energy, and the work-holding and positioning mechanism. Even though carbides and ceramics may be machined, the cutting tools may be made from cold-rolled steel or brass and are attached to the transducer so that they vibrate normal to the work surface. An abrasive suspended in water flows between the vibrating tool and the work piece. The

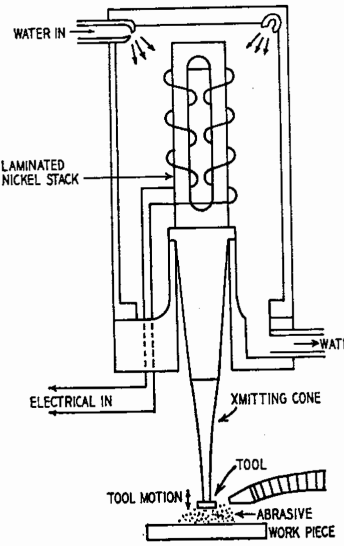


**Fig. 3—Electromechanical transducer.**

up-and-down motion of the tool drives the abrasive particles into the work, chipping it away. The work surface is worn away an almost negligible amount with each cycle of the tool motion, but the repetition rate of 26,000 per second produces a very significant rate of material removal.

## Electronic equipment

A simplified schematic diagram of the electronic driver and control equipment is shown in Fig. 2. It consists essentially of a master-oscillator-power-amplifier utilizing two 6L6 tubes (V1 and V2) as a push-pull electron-coupled oscillator. The capacitance of C1 is varied to tune the driver to the transducer operating frequency. An untuned transformer T1 couples the m.o.p.a. to the class-B power amplifier, utilizing push-pull 810's (V3 and V4) with approximately 500 watts output. A special output transformer T2 matches the 810's to the transducer load. An isolating network composed of C2 and L1

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permits application of a variable polarizing current to the transducer. Variation of this current enables the operator to control the ultrasonic power.

The polarizing current is a direct current applied to the transducer to permit operation on the most efficient part of the magnetization curve. It is applied through L1 which offers a high impedance to 26 kc and thus isolates the polarizing current power supply from the 500 watts of 26 kc power applied to the transducer. The capacitor C2 has a low impedance at 26 kc, allowing passage of the 500 watts, but prevents the d.c. polarizing current from flowing in the secondary of T2.

## The transducer

The heart of this machine tool is the ultrasonic transducer which converts electrical energy into mechanical energy of vibration or motion. A cross-section sketch of the transducer used on the first model of this equipment is shown in Fig. 3. In addition to the direct polarizing current, 26-kc electrical energy at approximately 80 volts and 6 amperes is fed into the coil wound around a stack of nickel laminations. For each ampere of current increase, the magnetic flux setup in the 4-inch nickel stack causes it to mechanically contract about one hundred thousandth of an inch. A decrease in current causes it to expand an equal amount in the manner previously described for the 10-kc oscillator. A sinusoidal change of current in the transducer coils will cause a sinusoidal variation in mechan-

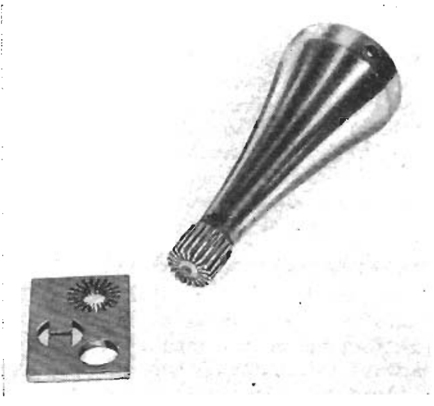

**Fig. 4—Sample of complicated machining on tungsten carbide, and tool used.**

ical length of the nickel stack. At the mechanical resonant frequency of 26 kc, the length changes about .001 inch.

Attached to the lower end of the nickel stack is a metal cone designed to transmit the vibrational energy to the tool. The cone is designed to increase the amplitude of vibration and provide a closer match or more efficient energy coupling between the tool and work piece. A good analogy is the tapered electrical transmission line in which the capacitance and inductance per unit length are varied to change its characteristic impedance. The mass and stiffness per unit length are changed so that the nickel stack is matched at one end of the cone, and the tool at the other end more closely matches the load placed on it by the cutting action.

## Tool cutting action

Although the maximum movement of the tool is only 0.004 inch, the acceleration is about $1.5 \times 10^5$g ($g = 32$ ft./sec.$^2$). This means that an object, the size and weight of a penny, when mounted on the end of the transmitting cone would exert a force of about one-half ton on the cone end. With the tremendous forces in play at the tip of the tool, it is not surprising that the abrasive and tool will eat their way into the work piece. The high acceleration given the abrasive particles is probably responsible for the cutting. Their extreme small motion gives a good surface finish and high accuracies.

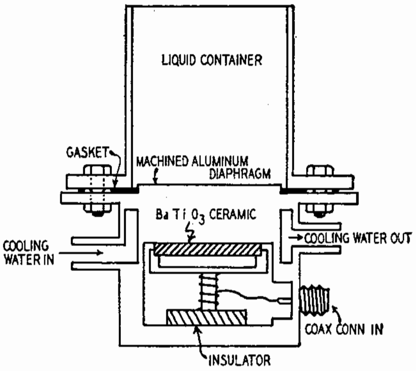


**Fig. 5—Ceramic transducer for propagation of ultrasonic energy into liquids.**

Even though the tool material is cold-rolled steel or brass, the machine readily cuts tungsten carbide, glass, quartz, and many other hard and brittle materials. The operations it can perform are unique in the machine-tool field. It can be mounted to drill holes of complicated cross-section as illustrated in Fig. 4. The ultrasonic machine tool is finding application in die-making, and other fields where the use of expensive diamond dust has before been the only method of machining.

## High-frequency ultrasonics

The practical physical dimensions of magnetostrictive materials limits the high frequencies at which a transducer made of this material can operate. It is therefore necessary to use either crystals or ceramics to obtain higher frequencies. In the study of propagation and absorption phenomena, frequencies in the order of 15 mc are commonly used. One megacycle is very good, since most liquids absorb large amounts of energy at that frequency. A 1-megacycle liquid treatment unit is now being developed which has as the transducer, an electrostrictive barium titanate ceramic. The equipment consists of a treatment cup, a barium titanate transducer, and an electronic driver.

## The barium titanate transducer

Barium titanate is a polycrystalline ceramic which exhibits ferroelectric properties below its Curie temperature analogous in the electrical case to magnetic properties which are known to exist in magnetostrictive materials. In its original state the ceramic is not piezoelectric. The piezoelectric behavior is introduced by applying a d.c. bias of 30,000 volts per centimeter with the directions of the electrical and mechanical axes depending on the direction of the polarizing field. When the d.c. field is removed there remains a residue polarization which may be as high as 90% of the saturation polarization. Therefore, there is no need for maintaining a fixed electric biasing field on the ceramic during operation.

Even though the ceramic can withstand high temperatures without changing its physical properties, the piezoelectric polarization is reduced at temperatures around 90°C, and becomes completely depolarized above the Curie temperature which is about 120°C. It is therefore necessary when using barium titanate as a transducer to have some form of cooling system that will keep the ceramic below 90°C.

Applying a small alternating voltage to the barium titanate will cause the ceramic to mechanically vibrate. If the frequency of the applied alternating voltage approximates a frequency at which mechanical resonance can exist in the ceramic, the amplitude of vibration is considerably larger. Since the ultrasonic intensity of a sound wave is directly proportional to the square of the amplitude, vibrating the ceramic at resonance will give a large ultrasonic intensity output.

The electromechanical coupling factor of barium titanate is much greater than that of quartz. The electromechanical coupling factor is the same as described for the magnetostrictive transducer. It represents the percentage of the total electrical energy applied to the crystal or ceramic which is stored in mechanical form. For quartz the electromechanical coupling factor is about 1.1%, whereas in barium titanate it may run as high as 30%.

One advantage barium titanate has over quartz is the low impedance of the ceramic which allows it to operate at low driving voltages. Another advantage that barium titanate has over quartz when being used as a transducer is that the transducer can be made to any desired size or shape. The ceramic can be molded in the shape of a focusing radiator which will concentrate ultrasonic energy in a given region.

## A one-megacycle treatment unit

Fig. 5 shows the liquid treatment unit with the ceramic transducer mounted against an aluminum diaphragm. The ceramic is 2 inches in diameter and has a thickness of 0.100 inch. The diaphragm is designed to couple a maximum of ultrasonic energy to the liquid. This is accomplished by making the diaphragm an integral number of half waves thick. For aluminum at 1 mc a half wavelength is 0.32 cm or 0.126 inch. The diaphragm in the present liquid treatment unit is two wavelengths thick or 0.504 inches. This thickness gives the diaphragm sufficient cooling surface to keep the ceramic from overheating while in operation. A special grease is used to bond the ceramic to the diaphragm, with enough pressure being applied by a spring to keep the ceramic in contact with the diaphragm. A metal contact which supplies the alternating voltage to the transducer is made so that the ceramic is constrained as little as possible while vibrating, and at the same time prevents the ceramic from slipping. The water cooling system serves to keep the diaphragm, which is in contact with the ceramic, at a temperature low enough to prevent the ceramic from becoming depolarized. The liquid treatment unit is at ground potential with the high potential lead connected to the ceramic as shown in Fig. 5.

As was mentioned before, the low impedance of the ceramic permits 60 ultrasonic watts output with only 100 to 130 volts drive. Intensities of 3 watts per square centimeter are easily obtained. The unit shown in Fig. 5 can easily be adapted to continuous flow treatment or larger tank by bolting the transducer on the side or bottom of any large container. In this manner the transducer may be adapted to any liquid in almost any container. A great deal of information has been published on successful ultrasonic treatment of many liquids. In the field of chemistry, success has been obtained in the degassing of various types of liquids, vaporization of liquids, and the transformation of chemical compounds. A few biological effects are the destruction of protozoa and bacteria, loss of reproduction power to yeast cells, and loss of luminosity to luminous bacteria.

Since sound is such an integral part of sonar and similar underwater detection, it is highly probable that magnetostrictive oscillators will become increasingly important in depth sounding devices such as fathometers, and for military applications.

Many surprising and interesting effects are produced by high-intensity ultrasonic waves, but there yet remains a vast field of undiscovered phenomena of intrinsic value to society. It will pay to keep an eye on this field for new developments which are sure to come. END